Defending the Pondicherry interpretation: A response to Shafiee, Jafar-Aghdami, and Golshani

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Abstract

Recently Shafiee, Jafar-Aghdami, and Golshani (Studies in History and Philosophy of Modern Physics, 37, 316–329) took issue with certain aspects of the Pondicherry interpretation of quantum mechanics, especially its definition(s) and use(s) of "objective probability", its conception of space, the role it assigns to the macroworld in a universe governed by quantum laws, and its claim for the completeness of quantum mechanics. Here these issues are addressed and resolved.

Keywords: quantum mechanics; Pondicherry interpretation; objective probability; macroscopic; supervenience; space

1 Introduction

A decade ago it was pointed out by Dieks (1996) that

> the outcome of foundational work in the last couple of decades has been that interpretations [of quantum mechanics] which try to accommodate classical intuitions are impossible, on the grounds that theories that incorporate such intuitions necessarily lead to empirical predictions which are at variance with the quantum mechanical predictions. However, this is a negative result that only provides us with a starting-point for what really has to be done: something conceptually new has to be found, different from what we are familiar with. It is clear that this constructive task is a particularly difficult one, in which huge barriers (partly of a psychological nature) have to be overcome. Apart from finding a general and consistent interpretational scheme, there is the difficulty of "getting a feeling" for it; to attain a position in which one understands the interpretation... The sheer difficulty of the situation, in which the only thing that is certain is that familiar concepts do not work, surely is one central element of the particular situation in quantum mechanics.

Dieks further remarked that

> all these discussions [about the physical meaning of the mathematical formalism of quantum mechanics], both the original ones between the founding fathers of quantum mechanics and the more recent ones, were and are carried on in very small circles... Inside the small group of cognoscenti one faces the tremendous task of framing a new conceptual scheme that should replace the familiar ideas that are impressed upon us by everyday experience.

These observations are as true today as they were at the time they were written. The "Pondicherry interpretation of quantum mechanics" (PIQM) (Mohrhoff, 2000, 2001, 2002abcd, 2004ab, 2005b, 2006a) is a more recent attempt at this particularly difficult constructive task, in which huge barriers (arguably *largely* of a psychological nature, Mohrhoff, 2005a, 2006a) have to be overcome. As the architect of this interpretation, I can vouch for the difficulty (and importance) of "getting a feeling" for it. In my case—but this is probably true for most explorers of uncharted intellectual terrain—the "feeling" comes first. As Plato pointed out in the *Meno*, if discovery does generate novelties, it cannot arrive at its results through a reasoned procedure (Hamilton and Cairns, 1961). Campbell (1974) has put it this way: "When we venture beyond that which we already know, we have no choice but to explore without benefit of wisdom: blindly, stupidly, haphazardly" (p. 142).

The process of discovery can be described as an exchange between internal agents representing complementary interests—faithfulness of the articulation to what *feels* right on the one hand, and the demands of consistency and communicability (clearness, explicitness, etc.) on the other. In an apt simile, Blachowicz (1997) has compared the rhythm of proposal and disposal in scientific discovery to the exchange between a police artist and a witness. My published expositions of the PIQM from 2000 to the present mark different stages of this exchange, which continues. A critic of this interpretation is therefore presented with a potentially confusing variety of articulations of the same underlying "feeling".[1]

A critique of the PIQM was published in a recent issue of this Journal (Shafiee, *et al.*, 2006). The authors remark that "Mohrhoff's interpretation challenges one's intuition." I heartily concur. On the positive side, Shafiee, Jafar-Aghdami, & Golshani (SJG) maintain that I introduce "a new understanding of spatiotemporal events, the character of physical reality and the meaning of objective probability", and that

> this interpretation has some attractions. At least, some parts of the ontological attitude of Mohrhoff about the quantum world is fascinating. For example, his view about the supervenience of the reality of phenomena in micro-world on the events of macro-world or his metaphysical view about the 'space as the totality of existing spatial relations' deserves attention. Mohrhoff's interpretation decisively affects the way one observes the quantum world.

But whereas SJG rightly believe "that our understanding of the quantum phenomena should be compatible with all levels of physical description," they doubt that the PIQM "can satisfactorily supply such compatibility" and perceive "imperfections and incoherencies involved in Mohrhoff's conceptualization of space and time." The purpose of this article is to dispel these doubts and to explain why the perceived imperfections and incoherences only exist "in the eye of the beholder."

The four main concerns of SJG are my views on quantum-mechanical probabilities, space, the macroworld, and the completeness of quantum mechanics. These concerns are addressed in Secs. 2, 3, 4, and 5, respectively. The final section aims to take the mystery out of what is probably the most challenging feature of the PIQM—the supervenience of the microscopic on the macroscopic.

2 Probability

The PIQM is an interpretation of unadulterated, standard quantum mechanics. It is offered as an attempt to make sense of a hypothetical world in which the quantum-mechanical probability assignments are always exactly right, without nonlinear or stochastic modifications to Schrödinger's equation. It interprets a hypothetical world in which

[1] Blachowicz uses the word "meaning," as in "intended meaning" or "unarticulated meaning" (Blachowicz, 1994).

the reason why hidden variables are hidden is that hidden variables—be they local or nonlocal, contextual or noncontextual—do not exist. By the same token, it does not countenance absolute probabilities.[2] In addition it assumes that an arbitrarily small quantitative difference—for instance, the difference between probability 1 and a probability arbitrarily close to but less than 1, or the difference between off-diagonal matrix elements equal to 0 and off-diagonal matrix elements arbitrarily close to but unequal to 0, or the difference between exact bi-orthogonality and however-near bi-orthogonality—does not account for the significant difference between the possession of a property (by a physical system) or a value (by an observable) and the lack thereof. In other words, it interprets a hypothetical world without "elements of reality," in which neither probability 1, nor the diagonality of a reduced density-matrix, nor exact bi-orthogonality is sufficient for *is* or *has*.[3]

Then what is? According to the PIQM, to *be* is to be *measured*, and *any* event or state of affairs from which the truth or falsity of a proposition of the form "system S has the property P" (or "observable O has the value V") can be inferred, qualifies as a measurement. No property or value is possessed unless its possession is indicated by, or inferable from, an actual event or state of affairs. (There is no need for anyone to actually make the inference.) The properties of quantum systems are *extrinsic* in this particular sense. They *supervene* on property-indicating events (in this particular sense).

The quantum laws, accordingly, are correlation laws: they quantify correlations between (primarily) property-indicating events and (secondarily) properties indicated by events. Since the PIQM does not countenance absolute probabilities (cf. Footnote 2), the existence of correlations is tantamount to the dependence of the probabilities of possible outcomes on actual or assumed outcomes, rather than to the existence of *absolute* joint probability distributions that are non-factorizable. If we use the quantum-mechanical correlation laws to assign probabilities, we are free to choose (i) the actual or assumed outcome (or outcomes) on the basis of which we assign probabilities, and (ii) the measurement (or measurements) to the possible outcomes of which we assign probabilities. SJG are therefore right in saying that I differentiate between the laws of physics (qua

[2] The conditionality of quantum-mechanical probabilities was also stressed by Primas (2003), who draws attention to an axiomatic alternative to Kolmogorov's (1950) formulation of probability theory, due to Rényi (1955, 1970), pointing out that every result of Kolmogorov's theory, in which absolute probabilities have primacy over conditional ones, has a translation into Rényi's theory, which is based entirely on conditional probabilities.

[3] There is another reason why probability 1 is not sufficient for *is* or *has*. Implicit in every quantum-mechanical probability assignment is the assumption that a measurement is successfully made: there is an outcome. (After all, this is the reason why the probabilities of the possible outcomes of a measurement add up to 1.) This also holds in the special case in which the quantum-mechanical probability of a particular outcome equals 1. Quantum mechanics therefore yields probabilities with which this or that outcome is obtained in a successful measurement, not probabilities with which this or that property or value is possessed, regardless of measurements.

correlation laws) and the way we make use of them, but contrary to their assertion that, according to me, "probability assignments have to be considered as fundamental as the quantum laws themselves", I consider the correlation laws "more fundamental" than the probabilities we assign with their help (for once allowing "fundamental" to have a comparative).

The first exposition of the PIQM (Mohrhoff, 2000) was, as the title "What quantum mechanics is trying to tell us" suggests, a response to Mermin's (1998) exposition of the "Ithaca interpretation," which bore the title "What is quantum mechanics trying to tell us?". While it did not accept Mermin's division of reality into a physical and a non-physical part—at any rate, not for the purpose of making sense of quantum mechanics—it was nevertheless strongly influenced by his thinking at that time[4]. Mermin decided not to

> explore further the notion of probability and correlation as objective properties of individual physical systems, though the validity of much of what I say depends on subsequent efforts to make this less problematic. My instincts are that this is the right order to proceed in: objective probability arises only in quantum mechanics. We will understand it better only when we understand quantum mechanics better. My strategy is to try to understand quantum mechanics contingent on an understanding of objective probability, and only then to see what that understanding teaches us about objective probability... The aim is to see whether all the mysteries of quantum mechanics can be reduced to this single puzzle. I believe that they can[.]

Propelled by his belief that all the mysteries of quantum mechanics can be reduced to the single puzzle posed by the existence of objective probabilities, I decided, on the contrary, to explore that notion. My instincts were (and still are) that we will understand quantum mechanics better only when we have a better understanding of objective probability.

There are several reasons to consider quantum-mechanical probability assignments objective (in several respective senses):

1. They are based on objective, value-indicating events and objective physical laws.

2. They play an essential role even when there is nothing to be ignorant about.

3. They are needed to define and quantify an objective indeterminacy or "fuzziness." (According to the PIQM, the proper way to define and quantify a fuzzy state of affairs is to assign probabilities counterfactually, to the possible outcomes of *unperformed* measurements.)

[4] "Chris Fuchs has taught me to beware of conjoining 'objective' to 'probability'." (Mermin in Arndt, *et al.*, 2005).

4. They are not based on degrees of belief. (The stability of the hydrogen atom rests on the objective indeterminacies of its internal relative position and relative momentum, rather than on anyone's degree of belief or uncertainty about the values of these observables.)

How should one describe a quantum system *between* measurements short of transmogrifying a probability algorithm like the wave function into an evolving state of affairs? The PIQM stipulates that even the description of a quantum system between property-indicating events be based on property-indicating events. Suppose, for instance, that measurements have been made at t_1 and t_2, respectively, and that no measurements have been made in the meantime. The facts relevant to the description of the system between t_1 and t_2 are then all of the property-indicating events—in particular, the measurements made at t_1 and t_2—that bear upon the probabilities of the possible outcomes of measurements that could have been made (but were not) between t_1 and t_2 (Mohrhoff, 2000, 2001, 2004a). If assigning probabilities to the possible outcomes of unperformed measurements is the proper way to define and quantify an indeterminate or fuzzy state of affairs, this yields a description of a fuzzy state of affairs. Since this counterfactually described state of affairs, like every possessed property of the system, supervenes on property-indicating events, it would not be appropriate to conceive of it as a repository of *propensities*, inasmuch as propensities tend to be viewed as intrinsic.

Here, then, are two senses of "objective" in which (according to the PIQM) quantum probabilities do not qualify as objective:

1. Being single-case probabilities, they are not objective in the sense of being relative frequencies.

2. In spite of being single-case probabilities, they are not objective in the sense of being propensities.

In addition to giving reasons why (and why not) quantum probabilities are objective, I have argued that there are objective as well as subjective ways of using them (Mohrhoff, 2001). One arrives at an objective description of the indeterminate state of affairs that obtains between measurements if and only if, in assigning probabilities to the possible outcomes of unperformed measurements, all relevant facts are taken into account. In general this includes past as well as future events, for quantum mechanics allows us to assign probabilities on the basis of not only earlier *or* later measurement outcomes using Born's rule but also earlier *and* later measurement outcomes using the ABL rule[5] (Aharonov, *et al.*, 1964). If one assigns probabilities to the possible outcomes of unperformed measurements, with a view to describing a fuzzy state of affairs obtaining between measurements,

[5]The statement of the ABL rule in (Shafiee, *et al.*, 2006) is incorrect. In place of the absolute *values* in equation (1) there should be absolute *squares*.

without taking all relevant facts into account, one arrives at a description that is marred by a subjective element of ignorance. This subjective contamination is what makes some probability assignments subjective (in this particular sense).

The following statements by SJG are thus either liable to be misunderstood or incorrect, and if incorrect then due to either a misunderstanding on the part of SJG or an incorrect statement in one of my earlier paper. (My purpose here is to clarify rather than to sort this out.)

> [According to Mohrhoff] objective probability should not merely be attributed to actually observed measurement results.

Assignments of probabilities to the possible outcomes of *actually performed* measurements are, in fact, subjective in the last mentioned sense, inasmuch as they do not take into account the actual outcomes of such measurements. In this particular sense, only probabilities assigned to the possible outcomes of *unperformed* measurements can be objective.

> According to Mohrhoff, what the ABL rule basically shows is that for calculating quantum probabilities both the initial and the final states of the system are to be known.

This is an odd way of saying that if one wants to assign probabilities on the basis of earlier *and* later outcomes, then one has to use the ABL rule.

> One of the consequences of introducing objective probability in quantum theory is objective indefiniteness, in Mohrhoff's view.

This rather puts the cart before the horse. According to the PIQM, objective indeterminacy is a salient feature of the physical world. Assigning probabilities to the possible outcomes of unperformed measurements is merely a way—albeit the only one I know—of describing a fuzzy state of affairs.

> He considers probabilistic propositions in quantum mechanics to be counterfactual… in his view… the attribution of probability to the results of actually performed experiments is not appropriate[.]

As a matter of fact, probabilities can be assigned to the possible outcomes of both performed and unperformed measurements. (If probabilistic propositions were merely counterfactual, quantum mechanics would not be a testable theory.)

> [N]either correlations nor correlata have physical reality in Mohrhoff's view.

In truth, I consider the quantum-mechanical correlation laws as real as any fundamental physical law. The correlata are (primarily) value-indicating events and (secondarily) indicated values. They too form part of reality. It was Mermin (1998) who denied (physical) reality to the correlata. For him, their unreality was "an inescapable consequence of many different 'no-hidden-variables' theorems" which "require that if all correlations have simultaneous physical reality, then all the correlated quantities themselves cannot." (This corresponds to my denying reality to *unmeasured* values.) I know of no one who denies the reality of both the correlations and the correlata.

> Marchildon (2004) challenges Mohrhoff's speculation, since for him the non-valuedness of [an unmeasured observable] does not logically follow from a counterfactual construction of the ABL rule.

Although the non-valuedness of unmeasured observables is strongly suggested by the 'no-hidden-variables' theorems mentioned by Mermin, I never claimed that there is anything from which the non-valuedness of unmeasured observables follows *logically*. Marchildon concluded his (2004) with the words: "In the interpretation he has put forth, Mohrhoff has shown us a thought-provoking and original view of the way that, according to quantum mechanics, the world can be." His concerns are addressed in my (2004a).

> Kastner (2001) has... argued that Mohrhoff's application of the ABL rule... fail[s] to escape the conclusion of the proofs which state that the counterfactual usage of the ABL rule yields consequences that are inconsistent with quantum theory.

For refutations of these alleged "proofs" (Sharp & Shanks, 1993; Cohen, 1995; Miller, 1996; Kastner, 1999ab) see my (2001) as well as (Vaidman, 1999).

> [I]f we accept [Mohrhoff's] attitude, we must necessarily be committed to the irreducibility of the concept of probability... If the concept of probability is taken to be a non-reducible one, the realization of some counterfactual statements in the measurement process has no justification, save mere chance. But, to avoid a notion of objective chance, Mohrhoff introduces the concept of objective indefiniteness[.]

Neither do I wish to avoid the notion of objective chance, nor do I introduce the concept of objective indeterminacy for the purpose of avoiding this notion. The remainder of the passage is correct. To my way of thinking, possibility and its quantifiable cousin probability are irreducible concepts, and value-indicating events lack causally sufficient conditions (Ulfbeck & Bohr, 2001; Mohrhoff, 2002b, 2004a). The reason for the latter is that the probability of an event indicating a particular value V of a given observable O is the product of two probabilities: (i) the probability of the occurrence of an event indicating a possible value of O and (ii) the probability that the indicated value is V (given that a value is indicated). Quantum theory is exclusively concerned with probabilities of the latter kind. In assigning probabilities, it implicitly assumes the (actual or counterfactual) occurrence of a value-indicating event, and therefore it cannot account for it. And if it is fundamental, nothing can account for it, just as nothing can explain why there is anything, rather than nothing at all.

> [O]nce one considers objective probabilities to be statistical distributions over counterfactual statements, there appears a possibility of defining joint probabilities for incompatible quantities. One can take into account a complete set of eigenvalues of two incompatible observables, and if the statistical distributions do not refer to real events, one can define joint probabilities for the results of those two quantities[.]

Quantum mechanics is concerned with distributions over possible measurement outcomes. Even the possible outcomes of *unperformed* measurements are possible outcomes of *measurements*, and if measurements are incompatible in the actual world, they are also incompatible in all (nomologically) possible worlds. If, for instance, the x and y components of a spin-1/2 system are measured at the times t_1 and t_2, respectively, if both outcomes are "up", and if the system is not subjected to any measurement in the meantime, then the following counterfactuals are true:

- If the x component had been measured in the meantime (other things being equal), then the outcome "up" would have been obtained with probability 1.
- If the y component had been measured in the meantime (other things being equal), then the outcome "up" would have been obtained with probability 1.
- If first the x component and then the y component had been measured in the meantime (other things being equal), then the outcome "up" would have been obtained with probability 1 in both measurements.
- If first the y component and then the x component had been measured in the meantime (other things being equal), then the outcome "up" would have been obtained with probability 1/2 in both measurements.

All of these counterfactuals (and infinitely many others) contribute to describe the fuzzy state of affairs that obtains between t_1 and t_2. The same does not hold for counterfactuals whose antecedents are nomologically impossible (e.g., "if both the x and y components had been measured simultaneously in the meantime").

3 Space

The PIQM arrives at its ontological affirmations by analyzing quantum-mechanical probability assignments in different measurement contexts, rather than via an ontologization of mathematical algorithms or symbols. This is most straightforwardly done by adopting the approach popularized by Feynman (Feynman, *et al.*, 1965), according to which probabilities are added if alternatives are experimentally distinguishable, whereas amplitudes are added if alternatives are experimentally indistinguishable. In other words, if one wants to calculate the probability of a particular outcome of a measurement M_2, given the actual outcome of an earlier measurement M_1, one must choose a sequence of measurements that may be made in the meantime, and apply the appropriate rule:

- If the intermediate measurements are made (or if it is possible to infer from other measurements what their outcomes would have been if they had been made), one first squares the absolute values of the amplitudes associated with the alternatives and then adds the results.
- If the intermediate measurements are not made (and if it is not possible to infer from other measurements what their outcomes would have been), one first adds the amplitudes associated with the alternatives and then squares the absolute value of the result.

The *principal interpretational strategy* of the PIQM is now readily stated:

- Whenever quantum mechanics requires that amplitudes be added, the distinctions we make between the possible sequences of intermediate outcomes ("alternatives") are distinctions that "Nature does not make": they correspond to nothing in the real world; they exists solely in our minds.

The paradigm example is the two-slit experiment with electrons (Feynman, *et al.*, 1965, Secs. 1.1–6). It has been said that an electron—or a fullerene, for that matter (Arndt, *et al.*, 1999)—can go simultaneously through more than one slit.[6] How can it do this *without getting divided into parts that go through different slits*? It can do this because space is neither a self-existent (substantial) expanse nor does it have parts. If the setup demands that amplitudes be added, the distinction we make between the alternatives "the electron went through the left slit" and "the electron went through the right slit" has no counterpart in the real world. The reason this is possible is that the difference between the two alternatives rests on spatial distinctions that are not real *per se*. There is no intrinsic partition of space that forces the electron to choose which "region of space" to be in. Instead, the unity of the electron (or the *logical* unity of the fullerene's center-of-mass) militates against the conception of space as an intrinsically partitioned expanse.

[6] "Since both slits are needed for the interference pattern to appear and since it is impossible to know which slit the electron passed through without destroying that pattern, one is forced to the conclusion that the electron goes through both slits at the same time" (Encyclopædia Brittanica, 2006).

According to the PIQM, physical space is a set of relations; it contains—in the proper, set-theoretic sense of "containment"—the spatial relations that hold among material objects. The form of a composite object is the totality of its internal spatial relations. A particle lacking internal relations is therefore a formless rather than a literally pointlike object.[7] Space thus contains the forms of all things that have forms, but it does not contain the formless so-called "ultimate constituents of matter" (quarks and leptons, according to the Standard Model of particle physics). It is the web spun by their (more or less fuzzy) relations. Nor is there such a thing as *empty* space, not because space is teeming with virtual particles or vacuum fluctuations, but because unpossessed positions do not exist; where "there" is nothing, there is no *there*.

As said, fuzzy spatial relations (relative positions as well as relative orientations) are quantitatively described by assigning probabilities to the possible outcomes of measurements. What are the possible outcomes of a measurement of a continuous observable? Just as classical mechanics idealizes by assuming exact positions, so standard quantum mechanics idealizes by assuming that the possible outcomes of a position measurement correspond to a partition "of space." Because space is not an intrinsically partitioned expanse, spatial distinctions are relative and contingent: *relative* because the distinction between (what we conceive of as) two disjoint regions (e.g., inside R and outside R) may be real for one object and nonexistent for another (or for the same object at a different time); and *contingent* because the reality of that distinction for a given object O (at a given time t) depends on whether the corresponding proposition ("O is in R at t") has a definite truth value (either "true" or "false"), and this in turn depends on whether a definite truth value is indicated.

A particle detector is therefore needed not only to indicate the presence of a particle in the detector's sensitive region but also to *realize* (make real) the *distinction* between inside and outside that region, thereby making it possible to attribute to a particle the property of being inside or outside that region. Generally speaking, the measurement apparatus, presupposed by every quantum-mechanical probability assignment, is needed not only for the purpose of indicating the possession a particular property or value but also for the purpose of realizing a set of properties or values, which thereby become available for attribution.

SJG's presentation of these ideas is, to say the least, awkward. Particularly disturbing is their frequent use of the word "space" in place of "position," for example when they write that "space could exist for an object in a definite instant, but not existing [sic] for another object at the same instant and not existing for the same object at another instant" or that in the context of a two-slit experiment (for which it is appropriate to add amplitudes) one "can only talk about both the L and R slits as the space possessed by

[7] A pointlike form would be another hidden "variable."

the object."

SJG correctly point out that the detection of a single electron at the backdrop "does not say anything about the position of the electron in the whole L and R region" but then conclude erroneously that

> the statement 'The electron's position is in the entire region $L\&R$' is not true, because this statement cannot be justified by the indication of an individual particle.

In view of the relative and contingent reality of spatial distinctions, it is precisely *because* there is nothing[8] that indicates where exactly the electron passed the slit plate that the distinction we make between "through L" and "through R" has no reality as far as the electron is concerned.

Nor is it correct to assert, as SJG do, that said statement is "not consistent with the description given by quantum mechanics." All that SJG can justifiably assert is that the PIQM, which denies the existence of hidden variables, is inconsistent with whatever interpretational scheme SJG have at the back of their minds. If I guess correctly at their meaning of "probability space" and "real space," the same applies to their claim that the identification of the two spaces is "not compatible with what quantum mechanics describes."

Turning to the *Gedanken* experiment introduced by Einstein, Podolsky, and Rosen (1935) to argue that quantum mechanics is not a complete theory, SJG state, correctly, that "indication of position or momentum of particle 1 does not necessarily lead to [in fact, never amounts to] indication of position or momentum of particle 2." What I am unable to understand, and therefore compelled to disavow, is their attempt at an explanation:

> That is, if the measuring apparatus for particle 1 is macroscopic and has a sharp distribution, this does not permit us to consider the space for another object on the other side to be real. Otherwise, we encounter some kind of strong non-locality which prevents the spatial distribution of the measuring apparatus of the particle 1 to be sharp.

SJG go on to "demonstrate the deficiency of such a reasoning" by considering the case in which there is no spacelike separation, so that "there might be a local causal link between the two particles".

> If there could be a local causal link between the two correlated particles, while the physical properties of only one of them is indicated, what can one say about

[8]Nothing, that is to say, apart from the classical boundary condition that stipulates that the electron did not pass the slit plate anywhere but at the slits, or the fact that no electron passes the slit plate if both slits are shut.

> the physical properties of the other one? According to quantum mechanics, in such circumstances, the whole system is described by an entangled state.

For one thing, one can speak of the spacelike separation between two events such as measurements but one cannot speak of the spacelike separation between two particles. For another, since SJG assume that no direct measurement is performed on particle 2, the question of whether a measurement performed on particle 1 can be taken to indicate the possession of a particular property by particle 2, has nothing to do with the existence or nonexistence of a spacelike separation. If the two particles are correlated, then they are necessarily "described" by an entangled state, for saying that they are correlated is the same as saying that they are "described" by an entangled state—namely, that the joint probability distributions associated with the possible outcomes of direct measurements performed on *both* particles do not factorize. The conclusion that

> [o]nce one measures a correlated property for one of the particles, the same property is also measured indirectly for the other particle

may be justifiable within the interpretational scheme SJG have at the back of their minds, but it is not, under any circumstances, justified by quantum mechanics itself.[9] One gets a glimpse of that interpretational scheme when SJG notice "a gap between Mohrhoff's interpretation and a minimal causal description of quantum mechanics" and point out a difference

> between the two notions of indication and measurement (at least, in von Neumann's approach who describes the measurement as an interaction followed by a collapse)[.]

Anyone modestly familiar with the PIQM will be aware that it rejects not merely the notion of collapse but the very notion that is responsible for the conundrum of collapse—the notion of quantum state *evolution*. A quantum state $|\psi(t)\rangle$ is not an evolving, instantaneous state of affairs that obtains at the time t, and that collapses (or appears to collapse) at the time of a measurement. It is an algorithm that serves to assign probabilities to the possible outcomes of any measurement that may be performed—either actually or counterfactually—at the time t. The parameter t refers to the time of this measurement. Without reference to a measurement, it is ill-defined.

As for the gap between the PIQM and a minimal causal *interpretation* of quantum mechanics, that certainly exists. As said, value-indicating events lack causally sufficient conditions (Ulfbeck & Bohr, 2001; Mohrhoff, 2002b, 2004a). This alone is sufficient to conclude that the quantum-mechanical correlations between such events do not admit of

[9]By "quantum mechanics itself" I mean the mathematical formalism together with what Redhead (1987) has called the "minimal instrumentalist interpretation" (p. 44).

a causal interpretation. The search for a causal explanation of these correlations puts the cart before the horse. It is the laws governing these correlations that determine the extent to which causal concepts can be used. Such concepts are applicable only to the macroworld (see below), where the statistical correlation laws of quantum physics degenerate into the deterministic laws of classical physics, for this alone makes it possible to think of the correlata as causes and effects.

4 The macroworld

SJG maintain that both the Copenhagen interpretation and the PIQM "require something beyond a quantum process for attributing physical reality to the realm of micro-physics." While I cannot vouch for the Copenhagen interpretation, which comes in a variety of flavors, there is no such thing as a quantum process where the PIQM is concerned. It rejects the notion of a quantum process for the same reason that it rejects the notion of quantum state evolution. What there is, according to it, is property-indicating events, properties indicated by events, and the *macroworld*, which encompasses the property-indicating events as unpredictable changes in the values of macroscopic positions. Whereas the indicated properties owe their existence to the indicating events, the macroworld depends on nothing external to itself.

An explanation is in order. Let us note, to begin with, that no object ever has a sharp position (relative to another object).[10] Some objects, however, have the sharpest positions in existence. Moreover, the possibility of obtaining evidence of the departure of an object O from its classically predictable position[11] calls for detectors whose position probability distributions are narrower than O's—detectors that can probe the (intrinsically undifferentiated) region over which O's fuzzy position extends. Such detectors evidently do not exist for those objects that have the sharpest positions in existence. For them the probability of obtaining evidence of departures from the classically predictable motion is very low. Hence *among* them there are many of which the following is true: every one of their indicated positions is consistent with (i) every prediction that can be made on the basis of previously indicated properties and (ii) a classical law of motion. These are the objects I call "macroscopic". To permit a macroscopic object to indicate a measurement outcome, one exception has to be made: its position may change unpredictably if and when it serves to indicate an outcome.[12]

[10]In a non-relativistic world this is so because the exact localization of a particle implies an infinite momentum dispersion and hence an infinite mean energy. In a relativistic world the attempt to produce a strictly localized particle results instead in the production of particle-antiparticle pairs.

[11]By a "classically predictable position" I mean a position that is predicted by the appropriate classical law of motion on the basis of the relevant earlier property-indicating facts.

[12]Instead of being evidence of the fuzziness of the "pointer" position, such an unpredictable change is evidence of the counterfactual fuzziness of the observable measured—the fuzziness that would have

The positions of macroscopic objects—macroscopic positions, for short—indicate each other's values so abundantly, so persistently, and so sharply that they are fuzzy only in relation to an imaginary background that is more differentiated (spacewise) than the actual world. The region over which a macroscopic position is "smeared out" is never probed (by definition). Relating as it does to a purely imaginary background, its fuzziness is itself purely imaginary. The contentious question of whether macroscopic objects (properly defined) obey the classical *or* the quantum laws, is therefore ill-posed. Macroscopic positions obey both the classical and the quantum laws, inasmuch as the quantum laws degenerate into the classical laws whenever the fuzziness of observables can be ignored. Where macroscopic positions are concerned, this is *always*.

Within the interpretational scheme under discussion, the extrinsic nature of the values of physical observables is a consequence of their fuzziness. Because macroscopic positions are fuzzy only in relation to an imaginary background that is more differentiated than the actual world, or because (by definition) they never evince their fuzziness (through departures from classically predicted values), they are intrinsic not merely FAPP but for all *quantitative* purposes. At the same time they, too, are extrinsic. Even the Moon has a position only because of a myriad of effective "pointer positions" that betoken its whereabouts. Whereas we cannot, therefore, attribute independent existence to individual macroscopic positions, we *can* attribute independent existence to the macroworld, defined as the totality of relative positions between macroscopic objects.

In spite of having argued along these lines in several papers, SJG detect a "hidden role of observer in Mohrhoff's interpretation":

> one could declare that an indication without an observer has no meaning in the quantum domain, even if the classical objects are considered to be self-indicating... For without an observer, it cannot be verified if any property is really indicated for quantum systems.

Whereas every sufficiently comprehensive physical theory defines a set of nomologically possible worlds, no physical theory can differentiate between the actual world and another nomologically possible world (let alone account for the existence of the actual world). In classical physics we identify the actual world as the possible world whose initial (or final, or intermediate) conditions match the *observed* initial (or final, or intermediate) conditions. In quantum physics we identify the actual world as the possible world whose property-indicating events match the *observed* property-indicating events. Needless to say, it is as impossible to observe all property-indicating events as it would be to observe the complete initial conditions of a classical world (if such a world existed). My point here is that if the conclusion that classical physics presupposes conscious observers is

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obtained if no measurement had been made.

unwarranted, then the conclusion that quantum physics presupposes conscious observers is equally unwarranted.

In reality, we are not given a set of nomologically possible worlds and required to identify the actual world. We are given the actual world, whose laws define a set of possible worlds. The question is, do these laws admit the construction of a theoretical model that can be thought of as the model of a free-standing (Fuchs & Peres, 2000ab) or strongly objective (d'Espagnat, 1989, 1995) reality capable of existing *without* being given? In other words, can the "full elision of the subject" (Bitbol, 1990) be achieved? As far as classical physics is concerned, the widely accepted answer is a virtually unqualified Yes. According to the PIQM, the answer is equally affirmative where quantum physics is concerned. It is, however, considerably less straightforward to arrive at it. One has to decide which of the structures that can be constructed on the foundation of the mathematical formalism and its minimal instrumentalist interpretation (Redhead, 1987), describes what is independently real. There is no question in my mind that this can only be the macroworld.

So it is not quite on target to say without appropriate qualifications, as SJG do, that I believe in "a clear distinction between the micro and macro-worlds". A clear distinction there is, but it is like the distinction between a sequence and its limit rather than that between domains on either side of a boundary: among the world's more or less fuzzy relative positions, the *least* fuzzy are in a category of their own. Without ceasing to be extrinsic and governed by the laws of quantum mechanics, they are at the same time intrinsic *for all quantitative purposes* and governed by classical laws. Nor is it quite on target to say that "[a]ccording to Mohrhoff, the presence of the macroscopic world actualizes some realities in the microscopic domain" for, like the already quoted assertion that the PIQM requires "something beyond a quantum process for attributing physical reality to the realm of micro-physics", this suggests the existence of a microscopic domain of potential realities waiting to be actualized. The underlying viewpoint also finds expression when SJG state that

> we are always confronted with the question of how can one be assured of whether a measuring apparatus performs a measurement or not? For example, in Schrödinger's cat experiment, one cannot distinguish that the cat is dead or alive... when the cat is not observed and there is no perception of what was being measured[.]

Just as we are not given a set of nomologically possible worlds and required to identify the actual world, so we are not given a set of possible measurement outcomes (or a set of possible measurements each with its own set of possible outcomes) and required to identify the actual outcome. The need to account for the rather more persuasive reality of actual outcomes only arises if probability algorithms are misconstrued as physical states of some kind.

SJG miss "a quantitative criterion for defining the sharpness of a spatial distribution". I wonder why, since quantitative measures for the spread of probability distributions are common in standard probability theory. They further point out that we may not be able to distinguish between a sharp distribution and a non-sharp distribution. This is the reason why I defined "macroscopic" in a way that does not require that the probability of finding a macroscopic object where classically it could not be, be strictly zero. What the definition requires is that there be no position-indicating event that is inconsistent with predictions that could in principle be made on the basis of a classical law of motion and earlier property-indicating events. To be sure, we cannot be one hundred percent certain that a given object, however large or massive, falls in this category. Even if we had access to every existing record of its past whereabouts and knew all relevant boundary conditions, we might not be in a position to completely rule out the possibility of finding it where classically it could not be. But this does not affect the existence of macroscopic positions or their ability to indicate measurement outcomes. To the common objection that the probability of the "erasure" of a measurement outcome is never strictly 0, the PIQM replies that, by virtue of its definition of "macroscopic," a record created by an unpredictable, outcome-indicating change in the value of a macroscopic position is never erased (Mohrhoff, 2004b).

SJG asks whether one could "say that in the absence of the classical world there was no room for anything else to be in existence".

> We should not forget that we did not have a world obeying the rules of classical mechanics from the beginning. The existence of [a] classical world, with objects having sharp spatial distribution, requires certain conditions which have not been there all the time. For example, what kind of reality could one ascribe to fundamental particles in the early universe, when there was no indication? Apparently, Mohrhoff takes it for granted that the classical world has always been there and that it will exist in the future.

These are intriguing questions, to which I hazarded tentative answers in a paper that SJG seem to have missed (Mohrhoff, 2002d). We are familiar with the idea that the application of spatiotemporal concepts is limited to positive cosmological times. Given an expanding universe, this limitation is a consequence of a *classical* theory (general relativity). Quantum theory implies limitations on the applicability of classical concepts and (hence) on the validity of implications from classical theories. In particular, if we go sufficiently far back in cosmological time, we enter an era in which there is as yet no macroworld. If nothing happens or is the case unless it is indicated by macro events or states of affairs, then this entire era supervenes on the macroworld. It exists only because, and only to the extent that, it is indicated by goings-on in the macroworld. Thus instead of taking for granted that the macroworld has always been there, I assert that it has not.

The reality that one can ascribe to the properties of the universe at pre-macroscopic times is of the same kind as the reality that one can ascribe to the properties of a quantum system $\mathcal{S}$ between measurements.

To elucidate the similarity, I need to hark back to a point discussed in my (2004ab). As you will recall, the time on which a quantum state depends (in the Schrödinger picture) is the time of a measurement.[13] As far as the measured observable is concerned, it is the time at which the indicated value is possessed.[14] Unless the Hamiltonian is 0, the probability distributions describing a fuzzy state of affairs between measurements depend on the times of *unperformed* measurements. The antecedents of the counterfactual probability assignments describing this state of affairs are false not only because they affirm that a measurement is made but also because they affirm that this is made *at a particular time*.

How real is this particular time—or the distinction we make between *before* and *after* this time—as far as $\mathcal{S}$ is concerned? According to the PIQM, it is as real for $\mathcal{S}$ as the distinction we make between "through L" and "through R" is for an electron in a two-slit experiment that requires that amplitudes be added; that is to say, not real at all. A particular time exists for $\mathcal{S}$ if and only if it is the *indicated* time of possession of a particular property. As far as $\mathcal{S}$ is concerned, the time between successive actual measurements is only counterfactually differentiated (i.e., by unperformed measurements).

The reality that one can attribute to the pre-macroscopic universe is of the same kind, except that this era is prior to all measurements rather than situated between measurements. The relevant counterfactual probability assignments are therefore based on *later* outcomes (using Born's rule).[15]

5 Completeness

It is generally taken for granted that if quantum states are probability algorithms, then quantum mechanics is an incomplete theory.[16] This conclusion would be warranted if quantum-mechanical probabilities were defined as relative frequencies (which according

[13]The same goes for the time on which the "two-state" introduced by Aharonov and Vaidman (1991) depends. A two-state is to the ABL rule what an "ordinary" quantum state is to the Born rule.

[14]See Sec. 6 of my (2004a) for a discussion of the ambiguity of "time of measurement."

[15]In other words, the only density operator that one can meaningfully associate with the pre-macroscopic universe is an advanced or "retropared" one—a density operator that "evolves" toward the past in the same (spurious) sense in which a retarded or "prepared" density operator "evolves" toward the future.

[16]For instance: "The quantum wave function ψ might be merely a mathematical tool for calculating and predicting the measured frequencies of outcomes over an ensemble of similar experiments. . . However, even in the statistical interpretation, the 'measurement problem' in the more general sense remains. For quantum theory is then an incomplete theory that refers only to ensembles" (Bacciagaluppi and Valentini, 2006).

to the PIQM is not the case) or if quantum mechanics were incapable of encompassing the value-indicating events to which it serves to assign probabilities (which, as we have seen, is also not the case). What about SJG's objection that in "all interpretations that consider quantum mechanics to be complete and final… there are always certain questions that physics should not attempt to answer, as they go beyond the quantum description"?

No matter what the fundamental theory eventually turns out to be, as long as there is a fundamental theory, there will always be the mystery of its origin. A fundamental theory will always be incomplete in this minimal sense.[17] It will also be incomplete in the sense that it cannot explain why there is anything, rather than nothing at all.

As it is the objective of the PIQM to make sense of a hypothetical world in which the quantum-mechanical probability assignments are always exactly right, I take it for granted that the fundamental theory is quantum-mechanical in nature. If there are additional questions that quantum mechanics fails to answer, it is (I believe) not because the theory is incomplete but because *the physical world* is incomplete—as compared to certain theoretical expectations that have psychological underpinnings (Mohrhoff, 2005a, 2006a) but are physically unwarranted.

- Whereas the quantum-mechanical probability algorithm cannot provide sufficient conditions for the occurrence of value-indicating events, this signals the incompleteness of the theory only if such conditions nevertheless exist; otherwise it signals an "incompleteness" of the physical world.

- Whereas the use of causal concepts is confined to the macroworld, this signals the incompleteness of the theory only if a micro causal nexus nevertheless exists; otherwise it signals another "incompleteness" of the physical world.

- Whereas no values can be assigned to unmeasured observables, this signals the incompleteness of the theory only if unmeasured observables nevertheless have values; otherwise it signals yet another "incompleteness" of the physical world.

In fact, the incomplete differentiation of the physical world (spatiotemporal as well as substantial) is (i) a straightforward consequence of the principal interpretational strategy of the PIQM and (ii) one of its most significant implications. If in our minds we partition the world into smaller and smaller spatial regions, there comes a point beyond which there is no material object for which these regions, or the corresponding distinctions, exist. *Mutatis mutandis*, the same holds for the temporal and substantial distinctions we make (Mohrhoff, 2002d, 2005b, 2006a). They are warranted by property-indicating events, and the latter do not license an absolute and unlimited objectification of the former.

[17] If at all a fundamental theory can be explained, it is in weakly teleological terms. For quantum theory, such an explanation has been offered in my (2006b). For the Standard Model, it has been outlined in my (2002c).

6 Outlook

According to Schrödinger (1935), entanglement is "not... one but rather *the* characteristic trait of quantum mechanics." According to Misner *et al.* (1973), the central mystery of physics is the "miraculous identity" (p. 1215) of particles of the same type. According to Feynman *et al.* (1965, Sec. 1–1), the double-slit experiment with electrons "has in it the heart of quantum mechanics." According to Stapp (1975), Bell's theorem is "the most profound discovery in science." To my mind, all of these extraordinary features of quantum mechanics are subsumed and eclipsed by the supervenience of the microscopic on the macroscopic, which flies in the face of a twenty-five centuries old paradigm. It no longer is appropriate to ask: what are the ultimate building blocks, and how do they interact and combine?[18] Nor is the incomplete spatiotemporal differentiation of the physical world consistent with theoretical models that construct physical reality on the foundation of an intrinsically and completely differentiated spatiotemporal expanse, by associating physical properties with spacetime points.

According to the identity of indiscernibles, A and B are one and the same thing just in case there is no difference between A and B. There is no difference between two fundamental particles if each is considered by itself, out of relation to any other object.[19] Hence, considered out of relation to their relations, all fundamental particles are identical in the strong sense of numerical identity. In a well-defined sense, therefore, the number of "ultimate constituents" equals one. A similar conclusion can be reached by noting that the number of particles in a relativistic quantum system is a quantum observable. As such it is a property of the system as a whole, and it has a (definite) value only if (and only when) it is actually measured. In a well-defined sense, therefore, a relativistic quantum system is an intrinsically undivided whole, including the largest conceivable system—the physical universe.

The appropriate question to ask is: how does the Ultimate Constituent *manifest* itself? How does it take on properties? How does it constitute an apparent multitude of objects, and how does it realize their forms? Quantum mechanics (as seen through the eyes of the PIQM) suggest this simple answer: by entering into spatial relations with itself, the Ultimate Constituent gives rise to both matter and space, inasmuch as space is the totality of existing spatial relations, whereas matter is the corresponding (apparent)

[18] This follows not only from the extrinsic nature of the values of observables but also from the incompleteness of the world's substantial differentiation (Mohrhoff, 2002d, 2005b, 2006a).

[19] A fundamental particle considered by itself lacks internal structure and, hence, a form. Since motion is relative, we cannot attribute to it any of the properties that derive their meanings from the quantum-mechanical description of motion (that is, from external symmetry operations). Nor can we attribute to it any kind of charge, since charges derive their meanings from the quantum-mechanical description of interactions (that is, from internal symmetry operations). Quantum statistics, finally, rules out the association of distinct identities with objects lacking persistent and unswappable properties.

multitude of relata—"apparent" because the relations are *self*-relations.

If we equate the manifested world with the macroworld, then quantum mechanics affords us a glimpse "behind" the manifested world at formless particles and non-visualizable atoms, which, instead of being the world's constituent parts or structures, are instrumental in its manifestation. However, it allows us to describe what we "see" only in terms of inferences from macroevents and their quantum-mechanical correlations. If we experience something the like of which we never experienced before, we are obliged to describe it in terms of familiar experiences. By the same token, what lies "behind" the manifested world can only be described in terms of the finished product—the macroworld. I believe that this way of thinking makes the supervenience of the microscopic on the macroscopic a tad less mysterious.

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